CHAPTER 1

Mechanical Properties of Geopolymer Concrete by Using Fly Ash as Cement Replacement

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Abstract

Since the early 1900, engineers and materials technologist has involve in optimizing the concrete strength, though concrete has been used throughout history as a building material. With each successive development and corresponding strength increase, the definition of "high strength" was revised. According to the American Concrete Institute, high strength is defined as a concrete that has over 42MPa compressive strength. A versatile material, high strength concrete possess desirable properties other than high strength. This paper is to succinctly review the mechanical properties of geopolymer concrete. It includes the compressive strength, flexural and tensile strength. In order to obtain its mechanical properties of high strength concrete, the optimum mix must be identified and analyzed too. Taking into account the growing environmental problem of carbon dioxide emissions from the cement industry, this paper is focusing on using fly ash as the geopolymer material as the cement replacement. Instead of using Ordinary Portland Cement (OPC) as the binder, geopolymer paste can be used as the binder constituent. Geopolymer paste is highly recommended in the concrete production application as it is able to harden in 24 hours period and it has lower cost than OPC.

Keywords— high strength, geopolymer, mechanical properties, replacement, ratio of aggregate per binder

1.0 UTILIZATION OF FLY ASH

Coal-firing power stations generate one major solid waste which is fly ash. Considering from the power generations point of view, thermal electricity stations considered that fly ash is a waste material and they are looking for ways to exploit fly ash disposal in the most significant and economically advantageous way. First and foremost, the usage of the deposited fly ashes must be under expert advice since there are high content of toxic or heavy metals.

Recent study shows that the projected forecast for electricity usage in peninsular Malaysia will be produced from coal and gas (58% and 25%) by the year 2024 and electricity production in Malaysia leads to a whopping amount of coal fly ash some 6.8 million tons[1].

According to recent study, Fly ash is considered as a hazardous material, and the improper disposal of fly ash will not only increase the occupation of land but also deteriorate the environment and ecology. In last few decades, increasing efforts have been made towards the utilization of fly ash, especially in an efficient and green fashion[2]. Therefore, the utilization of fly ash as a raw material in cement manufacturing and as a partial replacement for cement in concrete has been the subject of great interest in an attempt to develop more sustainable cementitious materials.

In Malaysia, generating power results in a staggering production of bottom ash and fly ash with rates of 1.7 and 6.8 million tons annually respectively. According to Tenaga, Malaysia Electricity Supply & Voltage, by the year 2024, it is predicted that Malaysia will have to rely on coal and gas (58% and 25% respectively) to generate electricity. It is likely that the requirement for fossil and fuels could increase. This increase in utilization of coal will lead to generate of more coal ash that could eventually result in more environmental problems.

2.0 GEOPOLYMER CONCRETE

Geopolymer completely replaces cement in concrete and can be considered as an environment friendly construction material than Ordinary

Portland Cement (OPC) concrete. Geopolymer, the binding material in geopolymer concrete, is formed by alkali activation of amorphous alumino-silicate material under warm atmosphere. It has been reported that, the geopolymer concrete having compressive strength up to or even greater than 60 MPa could be easily produced [3]. Fly ash is one of the alumino-silicate materials for making geopolymer. Fly ash is generated as a waste product at thermal power stations and its effective disposal is a major concern across the world due to the environmental and health hazard issues caused by it. Use of fly ash as an alumino-silicate material for producing geopolymer binder is an effective method of utilizing a waste material. Geopolymer concrete is considered to be a promising construction material in place of cement concrete due to its better performance like resistance against acidic and sulphate exposure.

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The environmental benefits of fly ash stem from both the repurposing of a waste product, and the replacement of cement content in a given concrete mix design. The replacement of cement content can improve the overall environmental performance of a concrete mix design which is largely attributed to the fact that cement is the component of concrete that has the highest environmental impact, with 6–7% of global carbon dioxide (CO_2) emissions attributed to its production. The direct impact of using fly ash as up to 50% cement replacement on CO_2 reduction has not been calculated since the global warming potential impact category represents all emissions that are greenhouse gases and not just CO_2 [4].

Geopolymer concrete is considered to be a promising construction material in place of cement concrete due to its better performance like resistance against acidic and sulphate exposure [5]. Review papers indicate that concrete containing fly ash is proven to reduce concrete expansions as a result of alkali silica reaction as well as stronger resistance against sulfate attack as a result of both their physical effect on the microstructure as well as their influence on material chemistry [6], [7].

3.0 MECHANICAL PROPERTIES OF GEOPOLYMER CONCRETE

In this research studies on the mechanical properties of geopolymer concrete that have a few characteristic. According to the previous research there are discussed about the characteristic of geopolymer concrete which classified into compressive, flexural and tensile strength. Each property has its own specific characteristics influenced by the mixing process, casting and performance quality.

3.1 COMPRESSIVE STRENGTH OF GEOPOLYMER CONCRETE

Compressive strength test results are primarily used to determine that the concrete mixture as delivered meets the requirements of the specified strength f_c in the job description. Based on 45-55% content of fly ash in concrete, previous research, reported 39.29%, 29.2%, 8.2% and 2.72% reduction in the compressive strength of concrete specimens at ages of 3, 7, 28 and 90 days by partially replacing cement with 45% FA, respectively, at *w/b* ratio of 0.24. At *w/b* ratio of 0.19, the reduction reached 46.54%, 32.46%, 8.57% and 0.91%, respectively [8]. Lam et al. reported 36.1%, 18.19% and 13.29% reduction in the compressive strength of concretes containing 45% FA as cement replacement at ages of 7, 28 and 90 days, respectively, when *w/b* ratio was 0.19. At *w/b* ratio of 0.24, this reduction was 25%, 8.39% and 12.18%, respectively. At *w/b* ratio of 0.3, the reduction in the compressive strength at ages of 7, 28 and 90 days was 53.87%, 27.19% and 19.1%, respectively, whilst it was 54.13%, 37.87% and 21.96%, respectively, at *w/b* ratio of 0.5 [8].

Research conducted on 2012 by Siddique et al proved that 53.44%, 39.8% and 39.11% reduction in the compressive strength of concretes at ages of 7, 28 and 56 days with the inclusion of 50% FA as cement replacement as can be seen in Figure 1 [9].

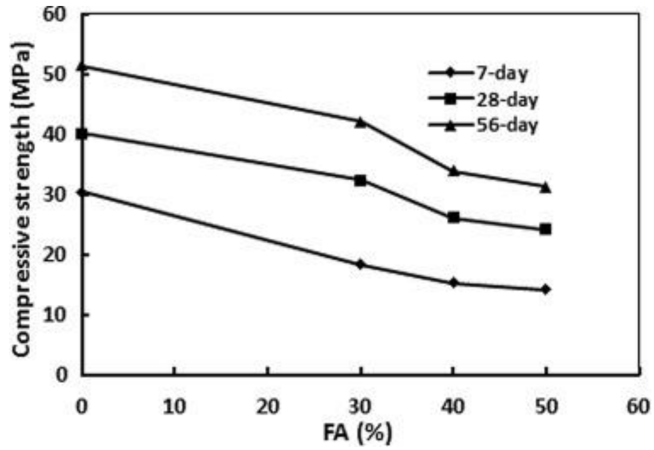


Figure 1: Effect of FA content on the compressive strength.

Based on 70% content of fly ash in concrete replacement, previous research reported 35.5%, 47.41%, 33.4% and 19.29% reduction in the 3, 7, 28 days and 3 months compressive strength of concrete specimens with the inclusion of 70% FA as cement replacement, respectively, when the curing conditions were 20 °C and has been illustrated in Figure 2 [10].

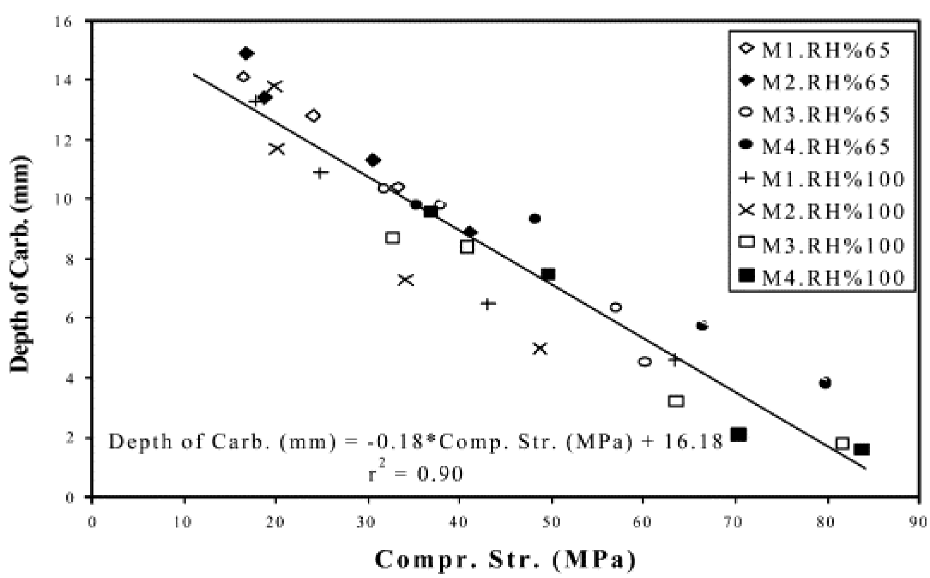


Figure 2: Relation between carbonation depth and compressive strength of fly ash concrete.

3.2 FLEXURAL STRENGTH OF GEOPOLYMER CONCRETE

Designers use a theory based on flexural strength. Therefore, laboratory mix design based on flexural strength may be selected from past experience to obtain the needed design modulus of rupture. Some also use modulus of rupture for field control and there are very few use flexural testing for structural concrete. Flexural modulus of rupture is about 10 to 20 percent of compressive strength depending on the type, size and volume of coarse aggregate used. However, the best correlation for specific materials is obtained by laboratory tests for given materials and mix design. Flexural strength is one measure of the tensile strength of concrete. It is a measure of an unreinforced concrete beam or slab to resist failure in bending. The flexural strength is expressed as *Modulus of Rupture* in MPa and is determined by standard test methods ASTM C78/C78M–16 (third point loading).

Previous research reported a reduction in the modulus of rupture of concretes at age of 28 days with the inclusion of FLY ASH as cement replacement. This reduction increased with increasing FA content [11]. Raffat Siddique also reported that a reduction in the flexural strength of concrete with the inclusion of 45% and 50% FA as cement replacement. The reduction in the flexural tensile strength at ages of 7, 28, 91 and 365 days was 47.37%, 42.59%, 29.1% and 23.64%, respectively, with the inclusion of 45% FA, whilst the inclusion of 50% FA caused 52.63%, 50%, 43.64% and 40% reduction, respectively as can be seen in Figure 3 [12].

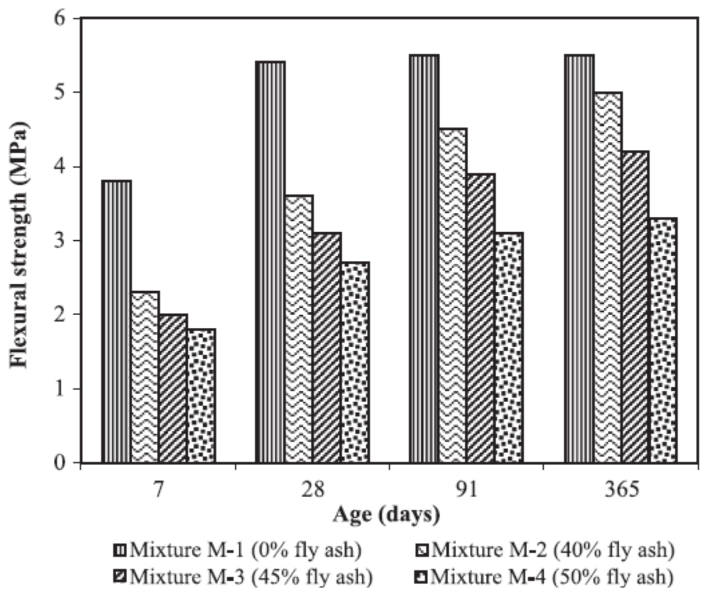


Figure 3: Compressive strength versus age.

There are research that has been conducted in 2013 reported that 0.41% and 1.96% reduction in the 7 and 28 days flexural strength of concretes with the inclusion of 60% FA as cement replacement, whilst 5.56%, 6.78% and 15.38% enhancement in the 56, 91 and 365 days flexural strength, respectively, was obtained when the original cement content was 340 kg/m^3. The inclusion of 80% FA as cement replacement caused 32.65%, 27.45%, 12.96% and 1.7% reduction in the 7, 28, 56 and 91 days flexural strength, respectively, whilst 3.1% enhancement in the 365 days flexural strength was obtained and can be referred to Figure 4 [13].

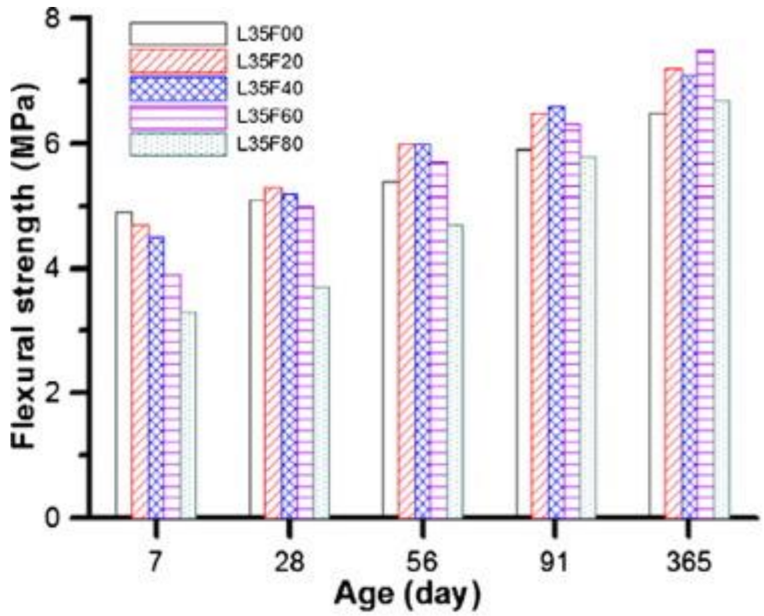


Figure 4: Effect of FA content on the concrete flexural strength.

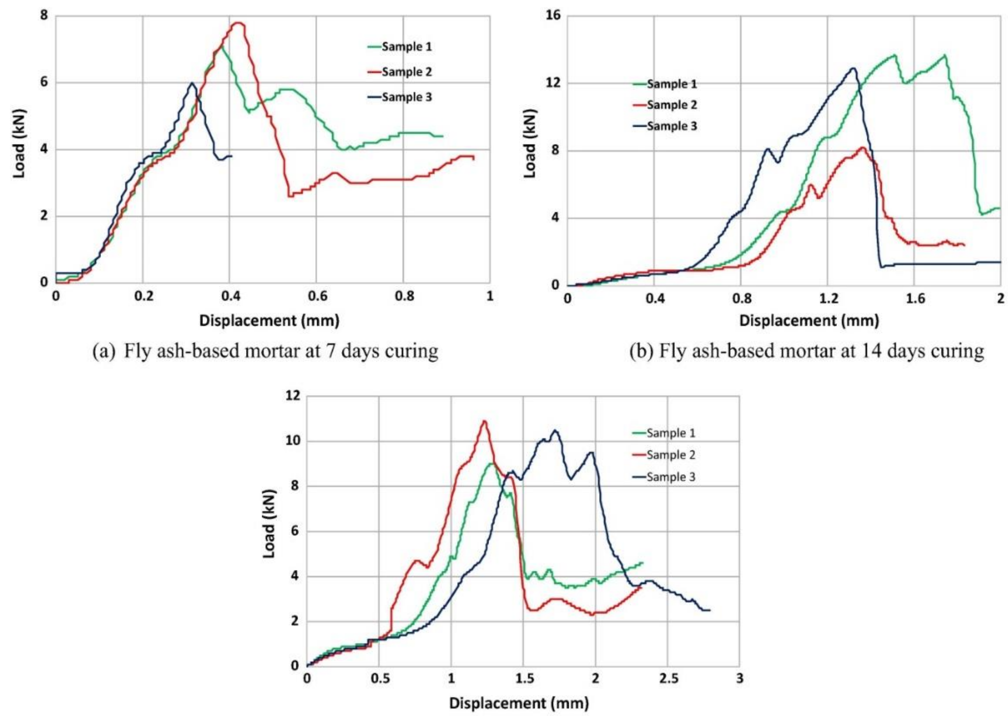
3.3 TENSILE STRENGTH OF GEOPOLYMER CONCRETE

Tensile strength is an important property of concrete because concrete structures are highly vulnerable to tensile cracking due to various kinds of effects and applied loading itself. However, tensile strength of concrete is very low in compared to its compressive strength. Currently, two methods named as direct tensile test and splitting tensile test are adopted to measure the tensile strength of concrete. The direct tensile strength is inclined to be used in specifications and guides as it is more realistic to reflect the tensile properties of concrete; however the test is difficult to ensure axial tension. The splitting tensile strength is more popular in research and engineering application as the test is simpler and more reliable with lower variation comparing with the direct tensile test.

Research conducted by Sahmaran and Yaman back in 2007 reported 21.23% and 9.24% reduction in the splitting tensile strength of concrete with the inclusion of 50% FA as cement replacement at ages of 28 and 56 days, respectively [14]. In another research also proved that there were reductions in the splitting tensile strength at ages of 28, 90 and 180 days with the inclusion of FLY ASH as cement replacement. The reduction in the 28 days splitting tensile strength was 20.5%, 27.22% and 35.7% with the inclusion of 50%, 60% and 70%, respectively, whilst it was 5.95%, 11.71% and 18%, respectively, at age of 180 days [15].

Siddique in 2004 reported a reduction in the splitting tensile strength of concrete with the inclusion of 45% and 50% FA as cement replacement. The reduction in the splitting tensile strength at ages of 7, 28, 91 and 365 days was 42.86%, 36.59%, 21.43% and 11.63% with the inclusion of 45% FA, respectively, whilst the inclusion of 50% FA caused 46.43%, 46.34%, 38.1% and 30.23%, reduction, respectively [12]. Besides that, in another research he conducted in the same year, he reported 35% and 45% reduction in the 28 days splitting tensile strength of concretes with the inclusion of 45% and 55% FA as cement replacement, respectively [16].

A research was conducted by Ernesto also proved that the specimen of concrete with fly ash-based that has been tested under tensile loading have a lower peak load and displacement at failure of specimens. The load-displacement curves of the specimen tested under tensile loading were presented in figures below [17].



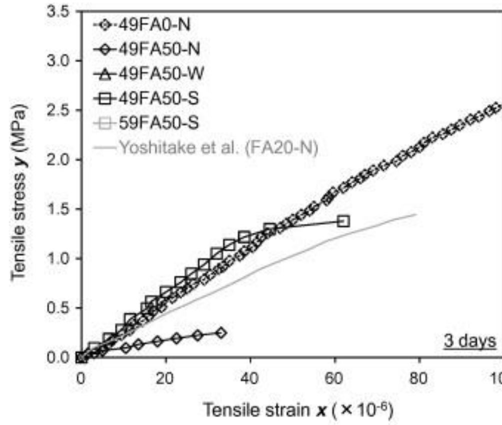
(a) Fly ash-based mortar at 7 days curing

(b) Fly ash-based mortar at 14 days curing

(c) Fly ash-based mortar at 28 days curing

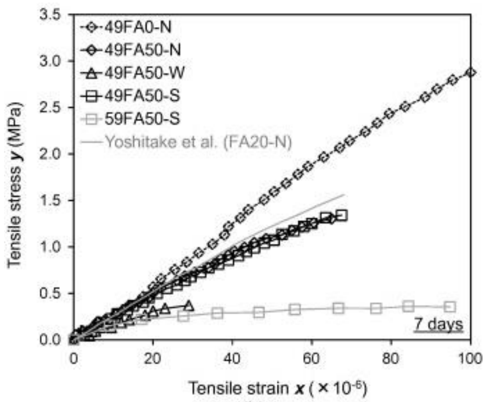
Figure 5: Tensile load-deformation curves of tested specimen (a) Fly ash-based mortar at 7 days curing (b) Fly ash-based mortar at 14 days curing (c) Fly ash-based mortar at 28 days curing.

Figure 6-8 show tensile stress-strain responses at the test age of 3, 7 and 91 days respectively from the previous study [18]. All responses are essentially linear until cracking at the maximum strain of each concrete in similar fashion as the previously reported test result. The stress-strain responses are affected by curing regimes and the concrete age at testing. These results represent the stress-strain responses reported before by Yoshitake et al. [19] to enable the comparison, where it reported that the observed results indicate both stress-strain responses are almost the same relation and other cases exhibited similar responses. The comparative results represent the difference of each of the linear responses. The report also concluded that the uniaxial tensile strength of fly-ash concrete at early age is higher than splitting tensile strength and the prediction.

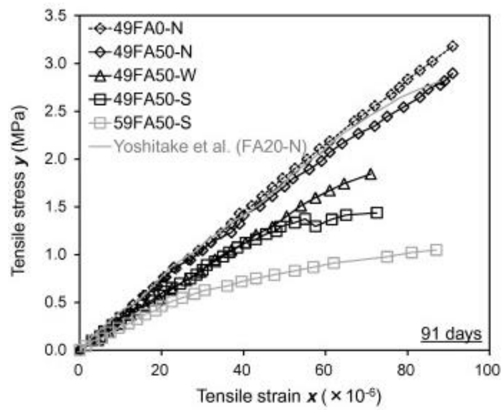


(a)

Figure 6: Stress-strain responses test age of 3 days.



(b)



(c)

Figure 7: Stress-strain responses test age of 7 days.

Figure 8: Stress-strain responses test age of 91 days.

On the other hand, previous research also indicated that the changes of mechanical properties of concrete subject to high temperature are dependent on materials as well as environmental factors (such as initial strength before exposure to high temperature, moisture content, and so on) [20]. The test results indicated that each temperature range had a distinct pattern of strength loss. It can be seen in the figure below.

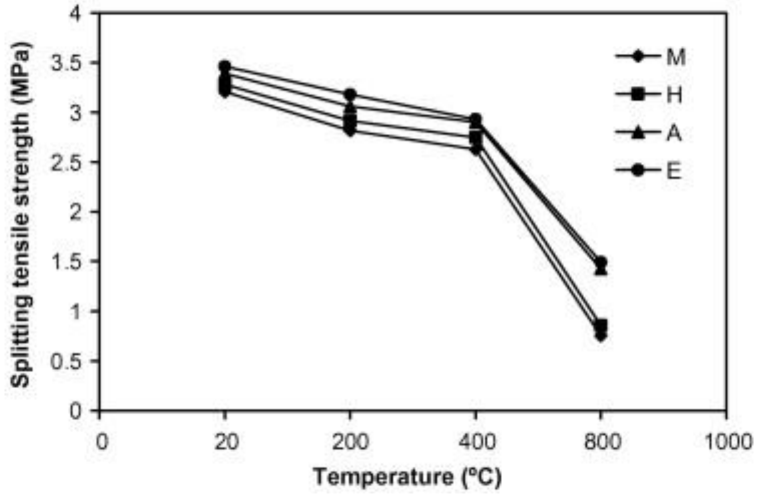


Figure9: Splitting tensile strength results after exposure to high temperature.

The fresh state properties of foam concrete were very much affected by the water content in the base mix, amount of foam added along with the other solid ingredients in the mix. Unlike normal weight concrete, the foam concrete cannot be subjected to any type of compaction or vibration which would affect its design density. Hence the important fresh state characteristics of foam concrete are consistency, stability and workability.

4.0 CONCLUSION

From the above reviews, it is evident that the inclusion of fly ash in the matrix decreased the strength especially at early ages. The strength significantly decreased with increasing fly ash content. Significant reduction in the strength was obtained during the early ages compared to the control. The strength gap between the fly ash mixtures and the control decreased with increasing curing age. At too long ages, the strength of fly ash mixture may reach the same or show higher strength value compared to that of the control. The time at which the strength of fly ash concrete will catch up with that of the control generally depend on the amount, reactivity and fineness of fly ash, *w/b* ratio and curing conditions such as humidity and temperature.

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